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Influence of uncertainty in heat–moisture transport properties on convective drying of porous materials by numerical modelling

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A B S T R A C T

The influence of uncertainties in heat–moisture transport properties, due to measurement errors and material heterogeneity, on the numerical simulation results of convective drying of two capillary-saturated porous materials is investigated by a transport-property parameter analysis (TP-PA), based on the Monte Carlo method. Here, the heat–air–moisture transfer model is evaluated many times, each time using a random set of one or multiple input parameters (i.e. transport properties), by which a stochastic model output is generated. The propagation of these transport-property uncertainties to the hygrothermal behaviour of the drying system is evaluated by statistical analysis of the model simulation output. The spread on the hygrothermal response is found to be strongly material dependent and is related to the dominant mode of moisture transport in the material, i.e. liquid or vapour transport. The TP-PA results clearly indicate that uncertainties in the heat–moisture transport properties can lead to significant differences in drying behaviour predictions, where differences of the total drying time with respect to its mean value up to 200% are found for the materials considered. Therefore, numerical modelling of heat and moisture transport in porous materials should preferably include a quantification of the propagation of these uncertainties, for example by means of the proposed transport-property parameter analysis. Such analysis, however, additionally requires detailed (a priori) experimental material characterisation to determine realistic uncertainty ranges.

Keywords: Convective drying; Porous material; Heat–moisture transport properties; Uncertainty; Stochastic; Material

1. Introduction

Heat and mass transport in porous materials is often analysed by means of numerical methods for various industrial drying applications, for food processing, for soil hydrological processes, for hygrothermal analysis of building envelope components, etc. Several numerical modelling approaches have been developed to model this coupled heat and mass transport, such as pore network models (e.g. Carmeliet et al., 1999; Metzger and Tsotsas, 2008; Prat, 1993; Yiotis et al., 2001) or macroscopic models (e.g. Ben Nasrallah and Perre, 1988; Defraeye et al., 2012; Erriguible et al., 2006; Janssen et al., 2007).

Abbreviations: CDRP, constant drying rate period; CHTC, convective heat transfer coefficient; CMTC, convective moisture transfer coefficient; DDRP, decreasing drying rate period; HAM, heat–air–moisture transfer; MCS, Monte Carlo simulation; TP-PA, transport-property parameter analysis; RH, relative humidity.

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In macroscopic models the porous material is considered as a continuum, where the transport processes are modelled by numerically solving the macroscopic conservation equations, which require knowledge of several heat–moisture transport properties. These properties are usually determined experimentally, often as a function of the moisture content. Material characterisation is thereby an integral part of numerical modelling with these macroscopic heat–air–moisture transfer (HAM) models. A significant spread on the required transport properties has, however, been reported when comparing results of different laboratories on multiple material samples (Dominguez-Munoz et al., 2010; Roels et al., 2004, 2010), especially for properties related to moisture transport. The resulting uncertainty in the transport properties originates from: (1) the measurement accuracy of the test setup; (2) material heterogeneity; (3) differences in measuring equipment, measurement protocol and data postprocessing between different laboratories.

The propagation of these transport-property uncertainties to the numerical simulation results of HAM models is often not assessed in detail. Usually, only simple sensitivity analysis of the HAM simulation results to individual transport properties is performed, e.g. by varying each property with a predefined percentage and assessing the impact on the results. Nevertheless, quantifying the influence of transport-property uncertainties, both for individual properties as well as for the ensemble of properties, on the simulation results is strongly recommended when comparing (validating) simulations with experimental data. Assessing this uncertainty propagation analytically is not straightforward since HAM models represent complex, non-linear systems with uncertainties in multiple transport properties. For such complex systems, methods based on Monte Carlo simulation (MCS) are more appropriate. In MCS, a deterministic model (e.g. a HAM model) is applied many times, each time using a random set of multiple input parameters with a certain probability distribution, by which a stochastic model output is generated. Thereby, MCS allows assessing uncertainty propagation of the input parameters by statistical analysis of the stochastic output. MCS, however, requires a large number of simulations.

Analysis based on the Monte Carlo method has already been applied for various drying applications of porous materials (e.g. Coppola et al., 2009; Cronin and Kearney, 1998; Tanaka et al., 2008). In this paper, the propagation of heat–moisture transport-property uncertainty to the coupled heat and mass transfer (HAM) simulation results of convective drying of a porous material is investigated by means of transport-property parameter analysis (TP-PA) based on the Monte Carlo method: the numerical (HAM) model is evaluated for a random set of one or multiple transport-property input parameters, by which a stochastic model output is generated. Such an analysis allows identifying in detail the sensitivity of the specific case to the heat–moisture transport properties. To the knowledge of the authors, such an analysis has not yet been performed. The transport-property uncertainty ranges, which serve as an input for HAM modelling, are estimated based on experimental measurements after which a TP-PA of convective drying of two capillary-saturated materials is performed, namely for ceramic brick and plaster. Afterwards, statistical analysis of the TP-PA output is performed to quantify the impact of these transport-property uncertainties on the drying process.

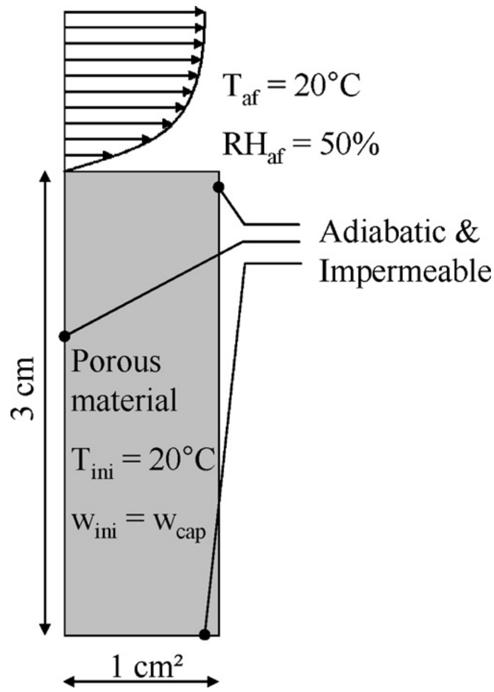

Fig. 1 – Computational model for numerical analysis of convective drying of a capillary-saturated porous material (subscript $_{cap}$) with initial (subscript $_{ini}$) and boundary conditions (w is the moisture content).

2. Methods

2.1. Configuration

The configuration used to evaluate convective drying of a capillary-saturated material is shown in Fig. 1. A porous material of 3 cm × 1 cm × 1 cm is considered. All side surfaces and the bottom surface of the material are considered adiabatic and impermeable for moisture. The porous material is assumed to be initially capillary saturated at a temperature of 20 °C where the top surface is exposed to air flow with an approach flow temperature (T_{af}) and relative humidity (RH_{af}) of 20 °C and 50%, respectively. The moisture content at capillary saturation, i.e. not fully saturated, can be determined by a free water uptake test (e.g. Roels et al., 2004). The two materials which are evaluated are ceramic brick and plaster. Both materials are capillary active but only plaster is considered hygroscopic. Detailed thermal and hygric transport properties can be found in Hagentoft et al. (2004) and are also specified in the next section.

2.2. HAM modelling

The configuration presented in Fig. 1 is used by the HAM model, where only one-dimensional transport is assumed. Convective heat and moisture transfer coefficients (CHTCs and CMTCs) are often used in HAM modelling. They relate the convective heat and moisture flux normal to the wall ($q_{c,w}$ and $g_{v,w}$, positive away from the porous material) to the difference between the wall temperature (T_w) or vapour pressure at the wall ($p_{v,w}$) and the approach flow temperature (T_{af}) or vapour pressure ($p_{v,af}$): CHTC = $q_{c,w}/(T_w - T_{af})$; CMTC = $g_{v,w}/(p_{v,w} - p_{v,af})$. The imposed CHTC and CMTC are 19.9 W/m^{2}K and 1.41×10^{-7} s/m, respectively, which are representative for exposure to the outdoor environment. An